Jets separated by a large pseudorapidity gap at the Tevatron and at the LHC

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XIII International workshop on Multiple Partonic Interactions at the LHC

The high-energy limit is defined by $\hat{s} \gg -\hat{t} \gg \Lambda^2_{\text{QCD}}$, where $\hat{s}$, $\hat{t}$ are the Mandelstam variables at parton-level, **the fixed-order pQCD approach breaks down**.

The perturbative expansion should be rearranged (symbolically) as,

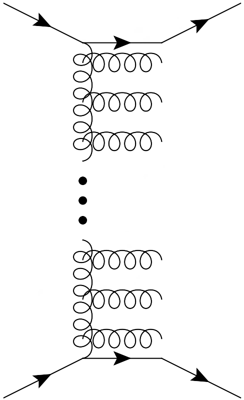
$$\mathrm{d}\hat{\sigma} \simeq \alpha_s^2 \sum_{n=0}^{\infty} \alpha_s^n \ln^n \left(\frac{\hat{s}}{|\hat{t}|}\right) + \alpha_s^3 \sum_{n=0}^{\infty} \alpha_s^n \ln^n \left(\frac{\hat{s}}{|\hat{t}|}\right) + \alpha_s^4 \sum_{n=0}^{\infty} \alpha_s^n \ln^n \left(\frac{\hat{s}}{|\hat{t}|}\right) + \ldots$$

such that $\alpha_s^n \ln^n (\hat{s}/|\hat{t}) \lesssim 1$.

Resummation of large logarithms of $\hat{s}$ to all orders in α_s via **Balitsky-Fadin-Kuraev-Lipatov (BFKL)** evolution equations of pQCD.

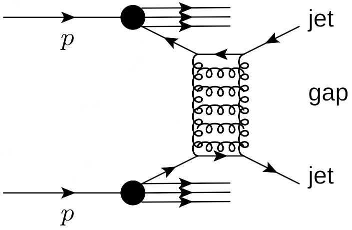
Resummation known at leading-logarithmic (LL) and next-to-LL accuracy.

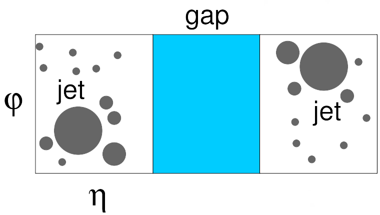
Very important test of QCD; very challenging to isolate experimentally



Multi-gluon ladder diagrams contribute significantly in the high-energy limit

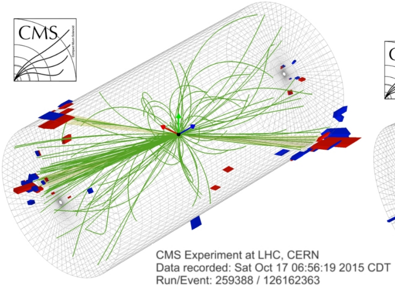
Mueller–Tang jets (a.k.a. "jet-gap-jet")



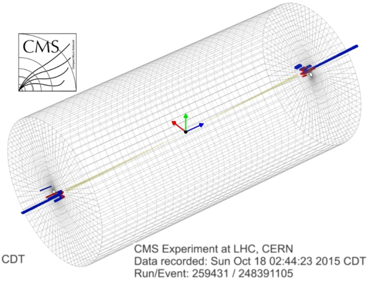


t-channel color-singlet exchange between partons (two-gluon exchange)
$\rightarrow$ η **interval void of particles between jets (pseudorapidity gap)**.

In the high-energy limit of QCD, process is expected to be describable by **Balitsky–Fadin–Kuraev–Lipatov (BFKL) pomeron exchange**.
A. Mueller and W-K. Tang, PLB 284 (1992) 123 (30 years ago!).



Color-exchange event candidate
(Background-like)

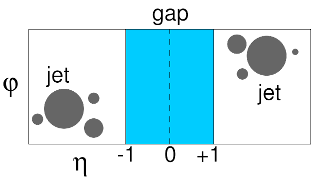


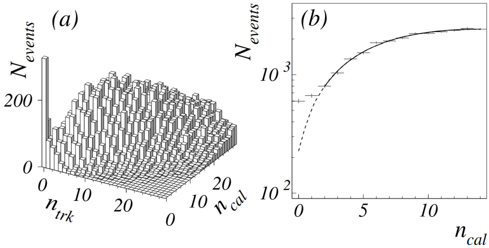
Color-singlet exchange event candidate
(Signal-like)

$\approx$ 0.6% of dijets with large rapidity separation are produced by t-channel color-singlet exchange at the LHC

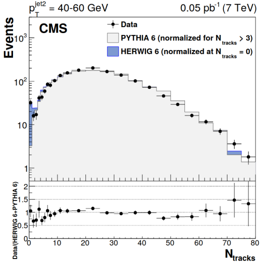
Ideal gap: **absence of particles between the jets.**

HERA, Tevatron, & LHC gap definition: **absence of particles with $p_T > 200$ (or 300) MeV between the jets**. Limited by reconstruction efficiency and noise threshold.





D0, PRL 72, 2332 (1994)



CMS, EPJC 78,242 (2018)

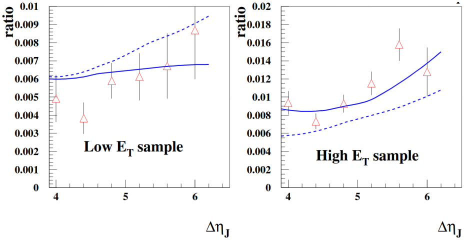
Fraction of color-singlet exchange dijet events (f_{CSE})

- Experiments have reported the fraction of CSE dijet events present in the inclusive dijet sample (originally suggested in A. Mueller and W-K. Tang, PLB 284 (1992) 123):

$$f_{\text{CSE}} \equiv \frac{d\sigma_{\text{CSE jets}}}{d\sigma_{\text{inclusive dijet}}} \tag{1}$$

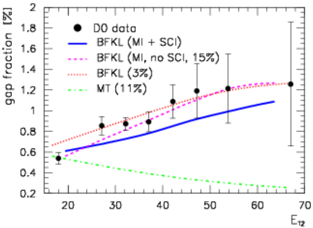
- Color-singlet exchange dijet cross section calculated at LL or NLL in BFKL.
- Inclusive dijet cross section is calculated with fixed-order LO or NLO + PS.

Pre-LHC studies with BFKL calculations at NLL with LO impact factors



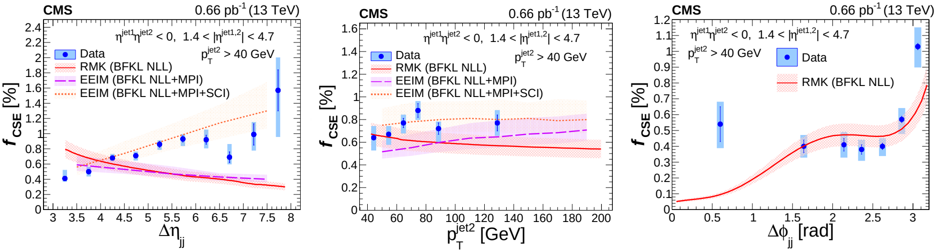
O. Kepka, C. Marquet, C. Royon
PRD 83.034036 (2011)

- NLL resummation with LO impact factor.
- Implementation in HERWIG6.
- K-factor for NLO corrections to inclusive dijets with `NLOJet++` package.



R. Enberg, G. Ingelman, L. Motyka
PLB 524 (2002) 273

- NLL resummation with LO impact factor.
- Implementation in PYTHIA6 with soft color interaction model.
- PYTHIA6 for QCD inclusive dijet.



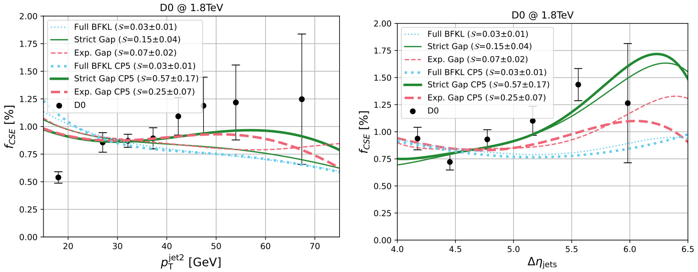
plots from CMS-TOTEM, Phys. Rev. D 104, 032009 (2021)

- 13 TeV measurement of fraction color-singlet dijet events as a function of jet p_T^{jet2}, $\Delta\phi_{jj}$ and $\Delta\eta_{jj}$.
- BFKL-only predictions have an opposite trend in data at 13 TeV.
- What changed from the Tevatron to the LHC?

- New PYTHIA8 subroutine for $qq \to qq$, $qg \to qg$, and $gg \to gg$ color-singlet exchange scattering with NLL resummation in BFKL framework.
- PYTHIA8 tuned to Run 1+2 LHC data, in principle better description of ISR, FSR, UE, and hadronization at the LHC.
- Parton-level BFKL NLL cross section calculated numerically and fit with empirical formula for implementation in PYTHIA8, cf Kepka, Marquet, Royon, PRD 83.034036 (2011) the amplitude can be calculated as

$$\mathcal{A}^{gg}(\Delta y, p_T^2) = \frac{16\pi\alpha_s^2(p_T^2)}{p_T^2} \sum_{p=-\infty}^{\infty} \int \frac{d\gamma}{2\pi i} \frac{[p^2 - (\gamma - 1/2)^2] \exp\left\{\bar{\alpha}(p_T^2)\chi_{\text{eff}}[2p, \gamma, \bar{\alpha}(p_T^2)]\Delta y\right\}}{[(\gamma - 1/2)^2 - (p - 1/2)^2][(\gamma - 1/2)^2 - (p + 1/2)^2]}$$

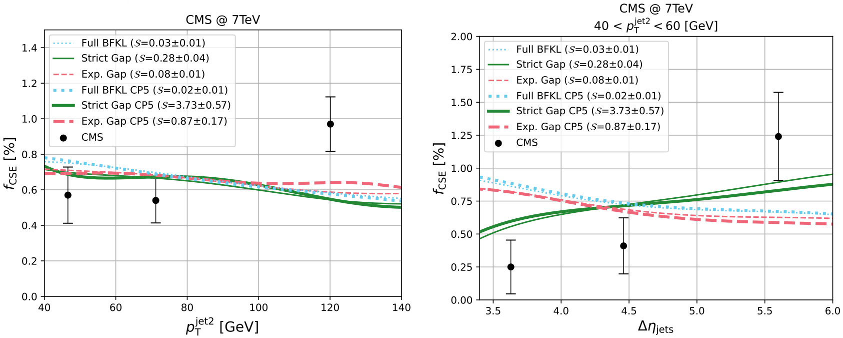
  χ_{eff} is obtained numerically by solving $\chi_{\text{eff}} = \chi_{\text{NLL}}(\gamma, \bar{\alpha}\chi_{\text{eff}})$.
- We simulate inclusive dijet events with fixed order NLO + PS (**POWHEG+PYTHIA8**).



data from D0, PLB 440 (1998) 189

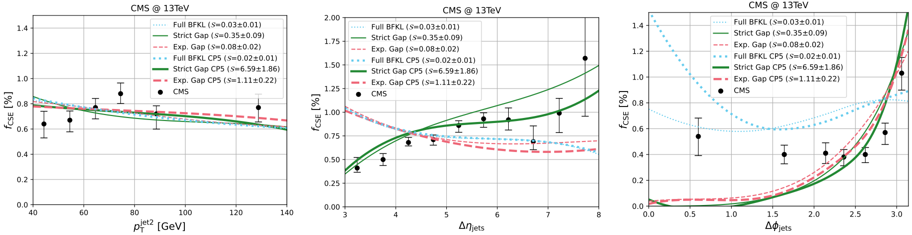
- BFKL pomeron exchange in PYTHIA8 (`ISR = on`, `MPI = off`). Inclusive dijet events with POWHEG+PYTHIA8 (`ISR = on`, `MPI = on`).
- Full lines: predictions based on theory-like gap definition ($N_{part} = 0$ in $|\eta| < 1$).
- Dashed lines: predictions based on D0 gap definition. ($N_{part} < 2$ in $|\eta| < 1$ with $p_T > 300$ MeV).
- Dotted lines: bare BFKL color-singlet exchange cross section, no rapidity gap requirement.
- Two PYTHIA8 tunes: CP1 without MPI and **CP5 with MPI**.

Comparison to CMS 7 TeV data



Data from CMS, EPJC 78,242 (2018)

- BFKL pomeron exchange in PYTHIA8 (`ISR = on, MPI = off`). Inclusive dijet events with POWHEG+PYTHIA8 (`ISR = on, MPI = on`).
- Full lines: predictions based on theory-like gap definition.($N_{part} = 0$ in $|\eta| < 1$).
- Dashed lines: predictions based on CMS gap definition. ($N_{ch} < 3$ with $|\eta| < 1$ with $p_T > 200$ MeV)
- Dotted lines: bare BFKL color-singlet exchange cross section, no rapidity gap requirement.
- More sensitivity to rapidity gap definition at 7 TeV than at 1.8 TeV. **Significant sensitivity to low p_T particle production modeling.**



Data from CMS, 13 TeV PRD 104, 032009 (2021)

$p_T^{jet1,2} > 40$ GeV, $1.4 < |\eta^{jet1,2}| < 5.2$, $\eta^{jet1}\eta^{jet2} < 0$. Anti-$k_t$ jets with $R = 0.4$.

- BFKL pomeron exchange in PYTHIA8 (`ISR = on`, `MPI = off`). Inclusive dijet events with POWHEG+PYTHIA8 (`ISR = on`, `MPI = on`).
- Full lines: predictions based on theory-like gap definition ($N_{part} = 0$ in $|\eta| < 1$).
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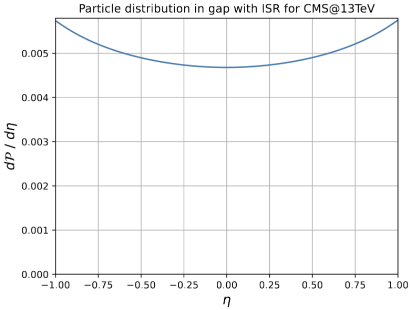
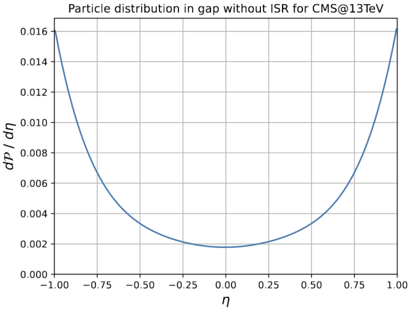
- Dotted lines: bare BFKL color-singlet exchange cross section, no rapidity gap requirement.
- **Significant sensitivity to low p_T particle production modeling in MC.**

ISR effects in color-singlet signal simulation

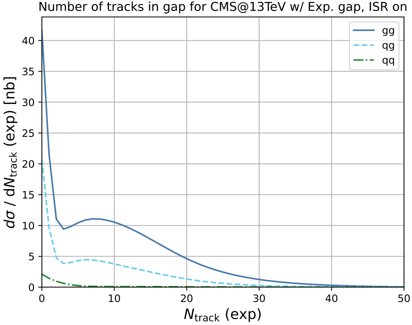


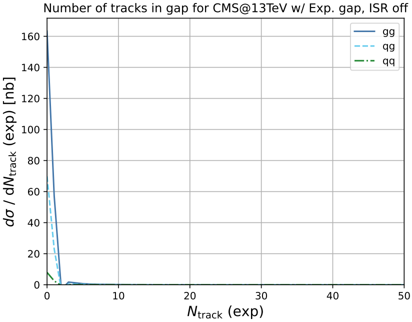


`ISR = on` $\rightarrow$ more particles between the jets.

`ISR = off` $\rightarrow$ fewer particles between the jets (unclustered hadrons at wide-angles).

ISR produces additional color charges in the forward-backward region $\rightarrow$ **net color-flow is reestablished.**
Is it phenomenologically reasonable/expected? Do we have data to constrain this independently of jet-gap-jet measurement?





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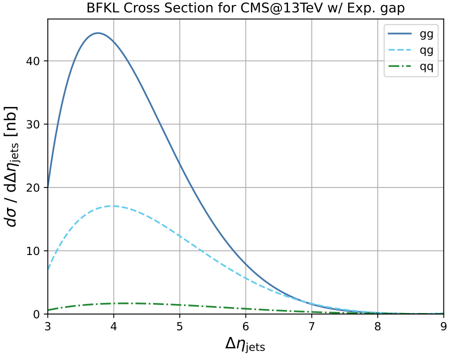
ISR produces additional color charges in the forward-backward region $\rightarrow$ **net color-flow is reestablished.**

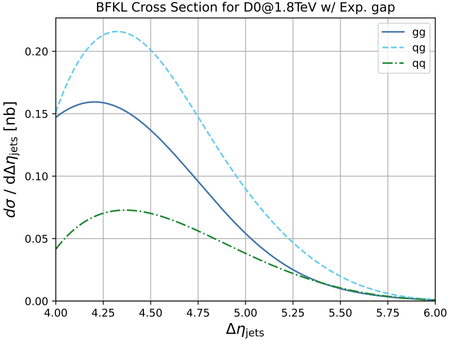
Effect is more prominent for $gg \rightarrow gg$ scatterings (color factors).

Parton flavor composition of color-singlet exchange dijet events

PDFs $\otimes$ color structure for color-singlet exchange $\otimes$ BFKL kinematical dependence



13 TeV



1.8 TeV

At 13 TeV, $gg \to gg$ dominates over $qg \to qg$ and $qq \to qq$.

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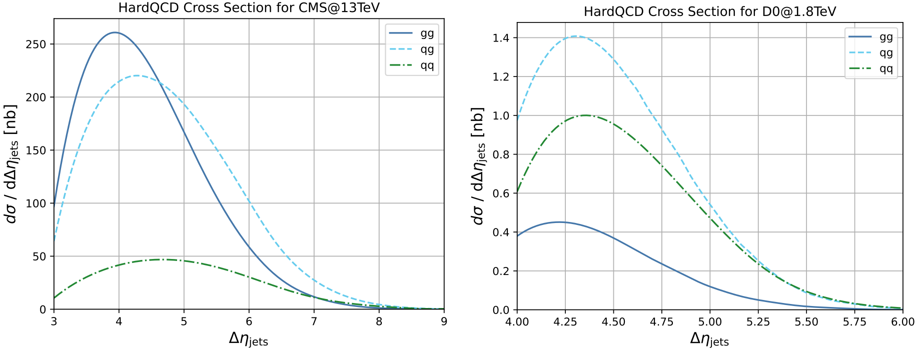
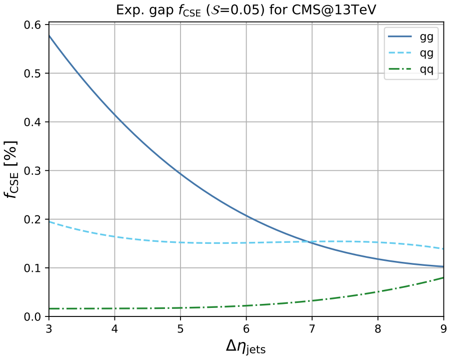
At 13 TeV, we are more sensitive to ISR effects for gluon-gluon processes.

Parton flavor composition of inclusive dijet events (PYTHIA8)

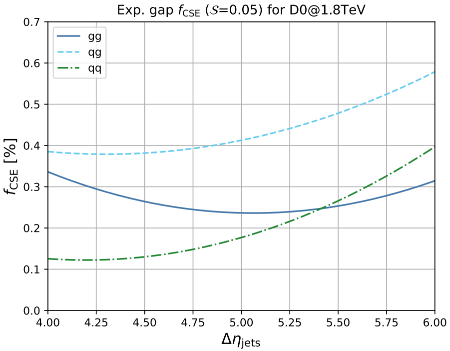


13 TeV 1.8 TeV

$qg \to qg$ and $gg \to gg$ dominate at LHC energies. $qg \to qg$ dominated at Tevatron energies.



13 TeV

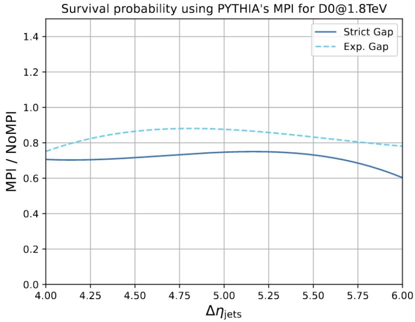


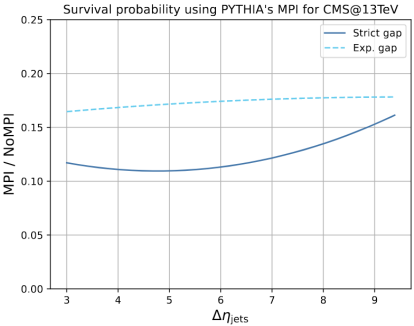
1.8 TeV

$gg \to gg$ by color-singlet exchange dominates at LHC energies, $qg \to qg$ by color-singlet exchange dominates at Tevatron energies.

The jet-gap-jet phenomenology relies on how well we simulate gluon radiation in Monte Carlo (for ISR and FSR).

- Jet-gap-jet measurements at the Tevatron and at the LHC require phenomenological interpretation. In principle, could be used to test BFKL predictions.
- Dijet production by BFKL color-singlet exchange has been implemented in PYTHIA8 as a new subprocess (NLL resummation + LO impact factors).
- Currently, the generation of color charges by ISR and their color reconnection is such that the rapidity gap is destroyed much strongly for $gg \to gg$ than $qg \to qg$ or $qq \to qq$.
- ISR with up-to-date PYTHIA8 tunes might not be adecuate for central rapidity gap signatures. Has to be cross checked with other processes with the same topology (e.g., J/ψ-gap-J/ψ), or jet-gap-jet process with different p_T thresholds for the gap definition.
- $\approx 0.6\%$ of dijets are produced by t-channel color-singlet exchange at the LHC, **currently we do not understand the mechanism by which they are produced.**





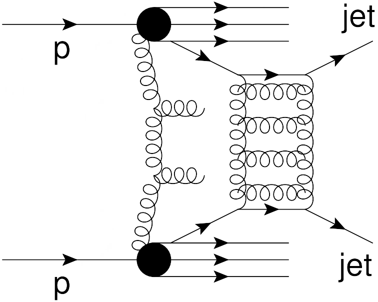
Proxy for the survival probability $\mathcal{S}$ calculated with MPI,

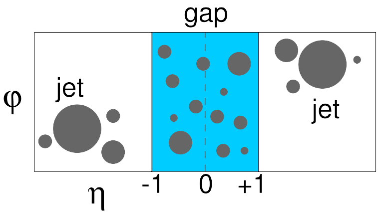
$$\mathcal{S} \equiv f_{\mathrm{CSE}}(\texttt{MPI = on})/f_{\mathrm{CSE}}(\texttt{MPI = off})$$

$\mathcal{S}$ from MPI is a factor of ≈ 10 (2) off w.r.t. fitted $\mathcal{S}$ values.

$\mathcal{S}$ is mostly flat as a function of $\Delta\eta_{\mathrm{jets}}$, consistent with typical assumptions that $\mathcal{S}$ decouples from kinematics.

The central η gap signature can be destroyed by MPI.





Previous phenomenological studies

BFKL at LL and NLL with LO impact factors: A. Ekstedt, R. Enberg, G. Ingelman arXiv:1703.10919, C. Marquet, C. Royon, M. Trzebinski, R. Zlebcik, PRD 87 (2013) 034010, O. Kepka, C. Marquet, C. Royon PRD 83.034036 (2011), R. Enberg, G. Ingelman, L. Motyka PLB 524,273 (2002), L. Motyka, A.D. Martin, M.G. Ryskin PLB 524 107 (2002), B. Cox, J. Forshaw, L. Lönnblad JHEP9910, 023 (1999)

Survival probability for jet-gap-jet events estimated with MPI (I. Babiarz, R. Staszewski, A. Szczurek PLB 771,532 (2017)), also MPI supplemented with soft color interactions (R. Enberg, G. Ingelman, L. Motyka PLB 524,273 (2002), A. Ekstedt, R. Enberg, G. Ingelman, arXiv:1703.10919).

Mueller–Tang NLO impact factors calculated by M. Hentschinski, Madrigal-Martínez, B. Murdaca, A. Sabio Vera: Nucl. Phys. B887, 309 (2014), Nucl.Phys. B889, 549 (2014), PLB 735,168 (2014).

NLO impact factors have yet to be implemented for phenomenological studies to complete the NLO calculation (BFKL@NLL + impact factors@NLO).

Previous experimental measurements on CSE process

We have over 20+ years of jet-gap-jet data in ep, $p\bar{p}$, and pp collisions:

HERA:

ZEUS: PLB 369 (1996)

H1: EPJC 24, 517 (2002)

Tevatron:

D0: $\sqrt{s} = 1.8$ TeV PRL 72, 2332 (1994), $\sqrt{s} = 1.8$ TeV PRL 76, 734 (1996), $\sqrt{s} = 0.63$ &1.8 TeV PLB 440 189 (1998)

CDF: $\sqrt{s} = 1.8$ TeV PRL 74, 855 (1995), $\sqrt{s} = 1.8$ TeV PRL 80, 1156 (1998), $\sqrt{s} = 0.63$ TeV PRL 81, 5278 (1998).

LHC:

CMS: 7 TeV EPJC 78,242 (2018), 13 TeV PRD 104, 032009 (2021)

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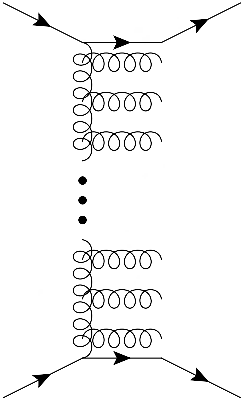
such that $\alpha_s^n \ln^n\left(\hat{s}/|\hat{t}\right) \lesssim 1$.

Resummation of large logarithms of $\hat{s}$ to all orders in α_s via **Balitsky-Fadin-Kuraev-Lipatov (BFKL)** evolution equations of pQCD.

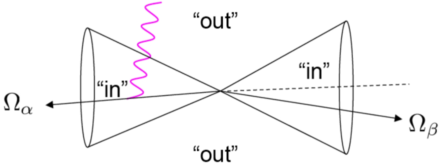
Resummation known at leading-logarithmic (LL) and next-to-LL accuracy.

Very important test of QCD; very challenging to isolate experimentally



Multi-gluon ladder diagrams contribute significantly in the high-energy limit

Other possible QCD effects that may be at play



Resummation of soft-gluon emissions at large angles is not taken into account in parton showers or in BFKL calculation.

When $p_T^{\text{jet}} \gg E_{\text{out}}$, resummation of $\alpha_s^n \log(p_T^{\text{jet}}/E_{\text{out}})^n$ becomes important.

The probability P_τ that the E_{total} emitted outside the jets boundaries is $E_{\text{total}} < E_{\text{out}}$ satisfies the Banfi–Marchesini–Smye (BMS) equation:

$$\begin{aligned}\partial_\tau P_\tau(\Omega_\alpha,\Omega_\beta) &= -\int_{\mathcal{C}_{out}} \frac{d^2\Omega_\gamma}{4\pi} \frac{1-\cos\theta_{\alpha\beta}}{(1-\cos\theta_{\alpha\gamma})(1-\cos\theta_{\gamma\beta})} P_\tau(\Omega_\alpha,\Omega_\beta) \\ &\quad + \int_{\mathcal{C}_{in}} \frac{d^2\Omega_\gamma}{4\pi} \frac{1-\cos\theta_{\alpha\beta}}{(1-\cos\theta_{\alpha\gamma})(1-\cos\theta_{\gamma\beta})} \underbrace{\Big(P_\tau(\Omega_\alpha,\Omega_\gamma)P_\tau(\Omega_\gamma,\Omega_\beta) - P_\tau(\Omega_\alpha,\Omega_\beta)\Big)}_{\text{soft-gluon emission}},\end{aligned}$$

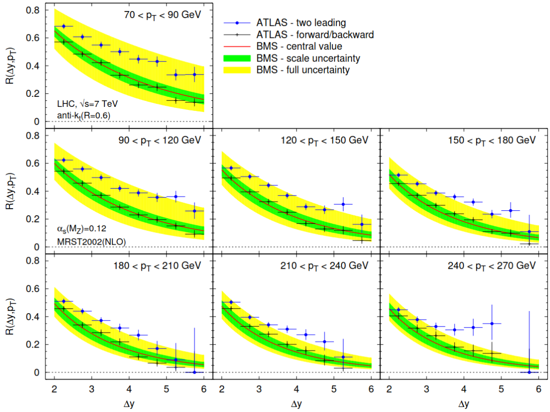
Events with at least two high-p_T jets separated by Δy.

Measure the ratio,

$$R(p_T,\Delta y) = \frac{d\sigma^{\text{veto}}/dp_T d(\Delta y)}{d\sigma^{\text{inc}}/dp_T d(\Delta y)}$$

where jets with $p_T > Q_0 = 20$ GeV are vetoed between the highest p_T jets in the numerator.

Soft-gluon resummation with BMS equation for jet-veto configuration.



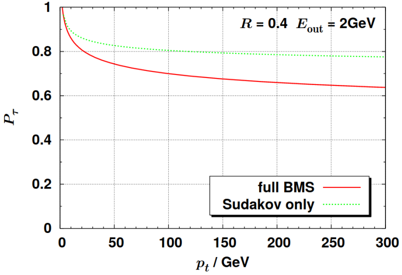
Y. Hatta, C. Marquet, C. Royon, G. Soyez, T. Ueda, D. Werder, Phys.Rev. D87 (2013) 054016

$$\frac{d\sigma}{d\Delta\eta d\bar{\eta} dt} = x_a x_b \tilde{f}_{eff}(x_a,t)\tilde{f}_{eff}(x_b,t)\frac{d\sigma^{q\bar{q}\to q\bar{q}}}{dt}\mathcal{S}P_\tau(\Omega_1,\Omega_a)P_\tau(\Omega_2,\Omega_b),$$

$$\tilde{f}_{eff}(x_a,t) = q(x_a,t)+\bar{q}(x_a,t)+\frac{N_c^2}{C_F^2}g(x_a,t)P_\tau(\Omega_1,\Omega_a)$$

$$\tilde{f}_{eff}(x_b,t) = q(x_b,t)+\bar{q}(x_b,t)+\frac{N_c^2}{C_F^2}g(x_b,t)P_\tau(\Omega_2,\Omega_b)\,.$$

Expressions valid in large-N_c limit



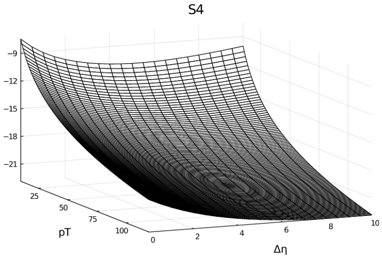
Y. Hatta, T. Ueda PRD 80 (2009) 074018

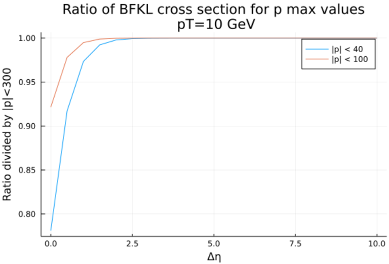
- Soft-gluon resummation is not included in BFKL calculation, although prescriptions for how these could be implemented have been presented e.g. by Y. Hatta, T. Ueda PRD 80 (2009) 074018.
- $gg \to gg$ contributions are more strongly suppressed after taking these effects into account (expressions valid in large N_c limit).

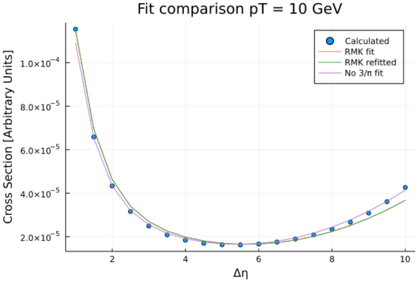
Following Kepka, Marquet, Royon, PRD 83.034036 (2011), the scattering amplitude for $qq \to qq$ is calculated as

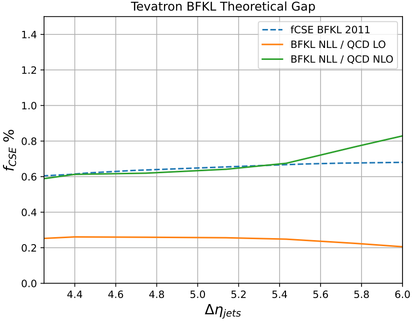
$$\mathcal{A}^{qq}(\Delta y, p_T^2) = \frac{16\pi\alpha_s^2(p_T^2)}{p_T^2} \sum_{p=-\infty}^{\infty} \int \frac{d\gamma}{2\pi i} \frac{[p^2 - (\gamma - 1/2)^2] \exp\{\bar{\alpha}(p_T^2)\chi_{\text{eff}}[2p, \gamma, \bar{\alpha}(p_T^2)]\Delta y\}}{[(\gamma - 1/2)^2 - (p - 1/2)^2][(\gamma - 1/2)^2 - (p + 1/2)^2]}$$

χ_{eff} is obtained numerically by solving $\chi_{\text{eff}} = \chi_{\text{NLL}}(\gamma, \bar{\alpha}\chi_{\text{eff}})$









Left: numerical calculation (blue markers). Red curve represents the previous fit, the magenta line represents the new fit.

Right:
The green curve is based on PYTHIA8 for jet-gap-jet divided by POWHEG+PYTHIA8 for inclusive dijets.

Agrees with O. Kepka, C. Marquet, C. Royon PRD 83.034036 (2011), calculated with HERWIG6 jet-gap-jet/`NLOJet++` inclusive dijets. The orange is for PYTHIA8 (LO+PS) for inclusive dijet.
Important to include NLO corrections for QCD jets.